REVIEW ARTICLE



The pertinence of Sutton's law to exposure science: Lessons from unconventional shale gas drilling

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Abstract

Sutton's Law urges the medical practitioner to utilize the test that goes directly to the problem. When applied to exposure science, Sutton's Law would argue that the major emphasis should be on techniques that directly measure exposure in or close to the human, animal or ecosystem receptors of concern. Exposure science largely and appropriately violates Sutton's Law by estimating exposure based on information on emissions or measurements obtained at a distance from the receptors of concern. I suggest four criteria to help determine whether Sutton's law should be violated for an innovative technology, and explore these criteria in relation to potential human exposure resulting from unconventional gas drilling (UGD): (1) The technological processes possibly leading to release of the chemical or physical agents of concern are reasonably understood; (2) the agents of concern are known; (3) the source and geographical location of the releases can be reasonably identified; and (4) there is information about the likely temporal pattern of the releases and resulting pollutant levels in relation to the temporal patterns of receptor susceptibility. For UGD, the complexity of the technology including many possible release points at different time periods; the existence of three variable mixtures of chemical and physical agents as well as possible unknown reactants; the demonstrated large variation in releases from site to site; and deficiencies in transparency and regulatory oversight, all suggest that studies of the potential health impact of UGD should follow Sutton's Law. This includes the use of techniques that more directly measure exposure close to or within the receptors of concern, such as biological markers or through community-based citizen science. Understanding the implications of Sutton's Law could help focus scientific and regulatory efforts on effective approaches to evaluate the potential health and ecosystem implications of new and evolving technologies.

Keywords Personal exposure · Emerging contaminants · Biomonitoring · Criteria pollutants · Inhalation exposure · Volatile organic compounds

Introduction

Willie Sutton was a bank robber who had a medical law named after him. Sutton robbed perhaps 100 banks in a notorious career that included numerous escapes from prison. His name lives on because he was reputed to have answered a journalist's question about why he robbed banks with an incredulous look and the statement "Because that's where the money is"

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Derived from this perhaps apocryphal story is a medical rule known as Sutton's Law. It refers to the importance of going directly to the medical test most likely to provide an accurate diagnosis. For example, the differential diagnosis of an enlarged lymph node includes infectious diseases, cancers, and immune disorders. Each could be evaluated indirectly through many time consuming and expensive medical tests—but Sutton's Law says just remove the lymph node and look at it under the microscope. Examples of reference to Sutton's law in the medical and public health literature include advice to focus on the mass lesion rather than on diffuse brain electrophysiological findings when operating for epilepsy [1]; consideration of the role of cellular analysis following bronchoalveolar lavage [2]; the argument that screening for HIV/AIDs should be focused on a narrow range of population groups that are at particular risk [3]; and that direct needle aspirates of the most involved

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site are preferable to external swabs in identifying the bacterial cause of skin infections [4].

I suggest that Sutton's law also applies to the question of whether to directly evaluate humans or ecosystems at risk from a technology rather than to extrapolate exposure levels by estimating or measuring emissions from the technology itself or the potential intervening pathways. I propose criteria to assess whether direct evaluation of receptors is appropriate, and use these criteria to explore the example of unconventional shale gas drilling (UGD). My conclusion is that Sutton's Law, by which I mean more direct measurement of potential human or ecosystem receptors, is relevant to exposure science, and particularly needs to be applied to the rapidly expanding UGD technology for which health effects have not been adequately studied despite much public concern.

Direct and indirect measures in exposure science

Exposure science has evolved to depend largely on indirect measures of estimating exposure to the receptors at risk. The father of occupational medicine, Bernardino Ramazzini, linked exposures to adverse health effects by simply observing the occupation of the worker. Occupational epidemiology was strengthened by qualitative classification of jobs to higher and lower exposure groups within the same industry, thus allowing within-group comparisons that improve identification of causative factors. With the advent of industrial hygiene as a discipline, a little more than a century ago, the development of techniques for pollutant

Fig. 1 Continuum for the emission of and exposure to a contaminant and the expression of a health effect

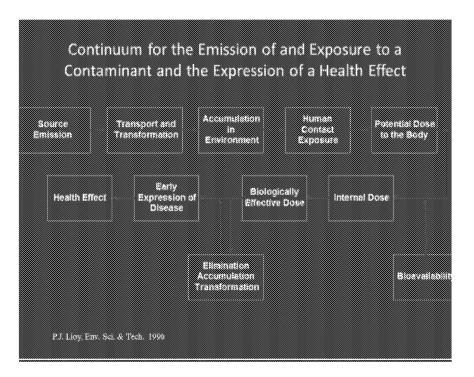
measurements allowed direct linkage with adverse endpoints of potential concern [5].

The environmental revolution increased the need for more sensitive techniques capable of measuring community exposure to pollutants in the general environment. The development of exposure science was enhanced by exposure assessment being recognized as a central component of the risk-assessment paradigm, which began to be formally instituted at EPA in 1983. This led to the formation of the International Society of Exposure Assessment (now the International Society of Exposure Science) in 1989 and the addition of organizational components or areas of emphasis to the Society of Toxicology, the Society for Risk Analysis, and the Society for Environmental Toxicology and Chemistry, among others. A hallmark of the success in the field has been scientific advances permitting the prediction of human exposures from distant sources, with sufficient reliability to develop regulatory approaches which protect public health and the environment.

Paul Lioy, a seminal thinker in the field, in 1990 published a figure showing the continuum from source to receptor (Fig. 1), which has changed little since it was first published [6, 7]. Exposure can be estimated from any point in the continuum leading to health effects. Sutton's Law would argue that it is most effective to estimate exposure as close as possible to the impact point.

Unconventional shale gas extraction

UGD has grown rapidly in the United States in the number of wells, the yield of natural gas and the geographical areas



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involved. UGD is usually defined as deep underground wells having a substantial lateral projection within the shale layer and requiring high volume hydraulic fracturing. Beginning with less than ten wells drilled by 2005, the total UGD wells in Pennsylvania had increased to 9300 by mid 2015, with another 7200 permitted [8]. The speed of development of a rapidly advancing technology in a populated area, without a recent history of oil or gas drilling, has led to significant public concern about exposure and health effects.

Partially driving this explosive growth are innovative technological developments that for the first time allows extraction of tightly bound gas in deep shale layers. Briefly, from a 6 to 10 acre well pad a deep vertical well is drilled as much as 2 km or more underground to reach a gascontaining shale layer; the pipe is bent to extend perhaps a kilometer or more within the shale layer; holes are blown through the lateral pipe; perhaps 20 million liters of an aqueous hydraulic fracturing mixture is injected under pressure to create fissures in the shale layer through which the gas is then extracted into the well. The hydraulic fracturing fluid contains a mixture of chemical agents, about 0.5-1.5% of the total volume, which includes compounds that help to extract the hydrocarbons from the shale, including preventing corrosion and the buildup of bacterial products. The hydraulic fracturing fluid also contains a physical agent, known as a proppant, to help keep the fissures open [9–11].

While hydraulic fracturing is decades old, the technology has rapidly and dramatically evolved. There is perhaps 100 times more fluid under higher pressure much deeper underground. The hydraulic fracturing agents also have changed. Further, the impact on adjacent communities is much greater as newer techniques allow eight or more wells to be sequentially drilled in different directions from the same drill pad, thus prolonging in the same neighborhood the period of intense drilling activity and attendant truck traffic, noise, and other unwanted components of UGD that contribute to public concern and reaction [12-14]. Along with the increased technical ability has come a spread of the shale gas drilling industry to more heavily populated areas. As described below, in addition to the marketable hydrocarbons and hydraulic fracturing agents, coming up from the well are aqueous solutions of the dissolved solids which must be disposed of safely.

What are appropriate criteria for violating Sutton's Law—and how do they apply to UGD?

Major advances in exposure science have greatly improved our ability to relate environmental releases and contaminant

Table 1 Criteria for violating Sutton's Law by not measuring exposures or effects in the receptors of concern

- 1. The technological issues resulting in the release of chemical or physical agents of concern by the specific industry are reasonably predictable
- 2. The chemical and physical agents of potential concern are known and measurable
- 3. The geographical location of releases in relation to the receptors of concern can reasonably be localized and identified
- 4. The temporal pattern and extent of releases in relation to potential receptors is predictable

levels in air, water, or food sources to the exposure of humans or of ecosystems at a distance from the emission site, thereby facilitating regulatory oversight and epidemiological studies that link exposure with effects. I suggest four criteria to justify this violation of Sutton's Law (see Table 1). For each I describe why violation of Sutton's Law for UGD is particularly problematic.

Criterion 1: The technological issues resulting in the release of chemical or physical agents of concern by the specific industry are reasonably predictable

Planning for the potential exposures to receptors from an industrial source is highly dependent on the specifics of the source, which are usually reasonably well understood. Assessment of emissions and monitoring of communities will differ depending upon whether the source of concern is a petroleum refinery, lead smelter, coal-fired power plant, etc. However, UGD is a particularly complex multi-step technological process, which has many different possible sources of pollutant release. An expert elicitation study to evaluate the risks associated with shale gas drilling that could burden the environment or human health produced a risk matrix listing 264 risk pathways that linked activities related to shale gas development to burdens those activities create, and six broader categories of intermediate impacts that could plausibly occur under normal operating conditions (including groundwater, surface water, soil quality, air quality, habitat disruption, and community disruption). The authors also listed 14 accident types [15].

Supporting the concept that there are many diverse potential release points from UGD operations is the recent EPA report on hydrofracturing impacts on water [9]. This report was summarized by Thomas Burke, the EPA Assistant Administrator for Research and Development, as finding "evidence that fracking has contributed to drinking water contamination in all stages of the process: acquiring water to be used for fracking, mixing the water with chemical additives to make fracking fluids, injecting the chemical fluids underground, collecting the wastewater that flows out of fracking wells after injections, and storing the

used wastewater" [16]. Similarly, there are a wide range of potential sources of air pollution from UGD [17].

A number of factors affect the likelihood that technological failures leading to release of physical or chemical agents will occur and will lead to adverse effects on humans or the environment. These include the internal safety culture of the industry and the extent of regulatory oversight. Nash found the shale gas industry to be relatively fragmented in terms of safety culture and to have a weak peer structure as compared to similar industries, such as chemical manufacturers [18]. Regulatory oversight is also relatively weak as the UGD industry shares the various loopholes in oversight accorded to the oil and gas industries in general, and has fought hard to beat back attempts to increase regulations [19]. Another issue specific to UGD is that emissions from individual sites usually do not exceed thresholds for regulatory oversight or reporting, that in the aggregate are easily exceeded by the many UGD activities in a local area [20]. For those technologies that have been stable over time, the accumulated safety history can be an important predictor of current and future risk. But, again, past history is not that informative as UGD technology and practices continue to rapidly evolve, including much larger volumes of water, higher pressures, newer hydrofracturing chemicals, and almost continuous changes in the corporate players involved. Perhaps most important is that rather than simply a gradual evolution in technology, UGD passed a tipping point when volumes of flowback fluids became too large to be handled routinely in wastewater-treatment plants, and deep underground injection of these fluids was complicated by seismic activities [21-24]. These wastes must now be handled largely at the surface in proximity to the human and ecological receptors of concern [25]. Storage and handling may occur at the UGD site or be trucked to collecting ponds or other storage or disposal facilities at a distance.

Criterion 2: The chemical and physical agents of potential concern are known and measureable

There are usually only a relatively limited number of chemicals or well-defined chemical mixtures that are released from an industrial source. But this is not true for UGD for which there are four sources of agents of potential concern: compounds added to facilitate hydrofracturing; hydrocarbons released from the shale layer; agents naturally present in the shale layers that are dissolved in the hydrofracturing fluid; and agents produced by chemical reactions within and among these three mixtures.

a. Hydrofracturing agents: In their recently released review, EPA reported that there were 1084 different hydraulic fracturing chemicals in use between 2005 and 2013, with between 4 and 28 used in each well

- during the 2011–2013 period [9]. Unfortunately, until recently it was generally not possible to readily find out what chemicals were used in each specific site. Even now, EPA reports that more than 70% of the time there is at least one compound held secret among the hydrofracturing agents for a given site based on the assertion of confidential business information [9].
- b. *Hydrocarbons*: The ratio of different hydrocarbon components of shale gas at a specific site can vary greatly. Wet gas has higher molecular weight alkanes and aromatics making it more suitable for use as precursors for the chemical industry. The aromatic component includes benzene, a known cause of human leukemia
- c. Dissolved agents: As shale is the residue of ancient seabeds, and the temperature underground is well over 240 °C, it is not surprising that this flowback water contains high concentrations of dissolved brine, often exceeding allowable disposal levels. Ions present in the brine can include strontium, iron, calcium, barium, boron, bromide, radionuclides, and cadmium [9, 10]. Where to put this flowback fluid, and lesser amounts of brine-containing fluids that continue to be produced during the working lifetime of the well, has been problematic, particularly in areas which are not geologically suitable for disposal in deep injection wells. In Pennsylvania, the demonstration of bromide coming through standard wastewater treatment facilities that had successfully treated lesser volumes of flowback water in the past led to a voluntary moratorium on the use of these facilities [21, 22]. However, the major alternative, the trucking of the waters to Ohio for deep injection was halted as a result of earthquakes, which have also been observed in Western states where deep underground injection has been the usual approach to flowback fluids [23]. Various methods, including recycling and storage are being used, but the problem of what to do with the large volume of potentially highly toxic agents brought to the surface initially and through the lifetime of the many wells in production remains challenging [24]. Despite the potential toxicity of flowback fluids being far greater than the added hydrofracturing compounds many state laws allow industry to maintain complete secrecy about these agents on the grounds that they are not intentionally added or that they are naturally present [25, 26]. Fortunately, as part of work on the exposome, there is increasing interest in detecting and measuring external agents through untargeted approaches.
- d. Products of chemical reactions: The likelihood of unknown reactants occurring within and among the large number of chemicals in the three mixtures listed above, and the challenges these pose to exposure

assessment, are greatly exacerbated by three factors relatively unique to UGD: (1) elevated temperatures in the underground space in which mixing occurs facilitate chemical reactions; (2) significant site-to-site variation in the components of all three of these mixtures depending on the choice of hydrofracturing agents and on local geographical factors; and (3) state laws that specifically absolve the UGD industry from responsibility to disclose any such reactants [25, 26]. In essence, there is little or no information about potential reactants on which to develop a monitoring plan.

Criterion 3: The geographical location of releases in relation to the receptors of concern can reasonably be localized and identified

An inherent assumption for most industrial sources of pollutants is that we know where they are located. This is generally also true for UGD sites. But two confounding factors present problems: (1) the many drill sites that individually may release relatively small amount of pollutants, as compared to a refinery, but which tend to accumulate in the hundreds or thousands in specific areas that can surround individual homeowners or communities; and (2) the fact that potential pollutant releases related to UGD activities extend beyond the drilling site and may include flowback disposal sites, such as, holding ponds; truck routes through which diesel exhausts and nitrogen oxide are emitted, and from which incidents leading to releases of hydrofracturing compounds or flowback constituents may occur; and pipelines and compressor stations.

Almost all of the studies reporting health effects associated with UGD use a surrogate measure of exposure based upon distance between home and drilling sites, which usually omits the off-site sources such as disposal ponds [27-33]. Further, even if the reported adverse finding in relation to distance between drilling sites and residences is replicated, the relevance of the findings to control measures is limited as the absence of information about specific pollutants leaves open which part of the UGD process needs to be rectified. A sophisticated study by Rasmussen et al., which reported asthma exacerbations in relation to a distance metric and to the temporal occurrence of drill site activities, both determined retrospectively, still leaves us without specific information as to the pollutants of concern thereby hampering choice of control options [32]. For example, the reported association with asthma may reflect diesel emissions from trucks, particularly those without the most efficient diesel control technology. If so, this would strongly support requiring only the more efficient diesel vehicles to be used earlier than now mandated.

The presence of literally thousands of UGD sites in a countywide area also presents a challenge to the placement of monitors. In essence, for those living in the midst of a shale play there is no downwind because of the large number and wide geographic dispersal of sources.

Also needing to be considered in developing a monitoring plan is that the potential impacts of UGD releases occur at different geographic scales: local, regional, and global. Air releases appropriately are of concern to adjacent residents and to the community-although community measurements may miss the impact on the fence line neighbors of the UGD site. Regional impacts include ozone precursors, a particular concern in areas which are on the borderline for exceeding the ozone standard [20, 34]. Particulate releases may also be significant but may be offset by natural gas replacing coal in upwind power sources. The impact of methane releases are properly evaluated on a global scale as this potent greenhouse gas will mix throughout the atmosphere during its multi-decade lifetime. Water pollution can occur locally affecting private wells that are common in rural areas. Regional water sources are also at risk during the delivery of hydrofracturing agents by truck and during the disposal of flowback fluids in ponds or other locations [9, 16, 24, 35].

Criterion 4: The temporal pattern and extent of releases in relation to potential receptors is predictable

For most industrial sources the temporal pattern of pollutant emissions is reasonably well understood, although unanticipated problems may produce unexpected releases. Such predictability facilitates the design and execution of exposure assessment programs. But uncertainty about the temporal pattern of significant releases, as well as the amount of these releases, is the norm for UGD [36, 37]. For example, in a landmark study with cooperating industries, Allen et al. found marked variability in methane emissions from site to site during flowback and during subsequent uploading episodes that often occur during the lifetime of the operating well [36]. In this study, during 27 completion flowback events, methane emissions ranged from less than 0.01 Mg to more than 17 Mg. Further, potential total emissions ranged from 0.2 Mg to 1 Gg—a 5000-fold difference. Similarly, average methane emission rates for a single unloading event ranged from about 100 g/min to over 30,000 g/min. The authors state that "At these emission rates, a single unloading event could, during the short period it is occurring, result in emissions that are the equivalent of up to several thousand wells in routine production" [36]. The authors also note that marked differences were observed in the emissions from two adjacent sites drilled by the same company. This variability is less important for methane,

which will mix world-wide during its many decade atmospheric residence. But, as other shale gas components, including benzene, would be expected to vary to the same extent as methane, the findings strongly suggest that local residents living near the high-emitting sites may be at risk in ways that are not readily discoverable by community or regional pollutant measurements, and that studies that look solely at one site, no matter how well done, cannot be generalized to all sites [38]. Not all UGD companies are willing to cooperate in providing advanced information to exposure scientists about the timing of either the flowback or uploading periods, and it is not unreasonable to assume that those companies willing to do so have better safety cultures than those who insist on secrecy. NIOSH scientists reporting on exceedances of the benzene standard in workers engaged in handling the flowback fluids similarly noted wide fluctuation in benzene exposure levels [37]. The impediments to temporal predictability are due to inherent technical aspects of UGD, limitations in industry transparency, and in regulatory oversight [25, 26].

Discussion

The conceptual basis and importance of studying biological markers of exposure is certainly not new and has been elucidated and expanded upon for the past three decades [38–40]. As previously predicted by Suk and Wilson [41], advances in molecular biology are being built upon to provide techniques better able to detect subtle differences related to exposure, to develop broader exposure concepts, such as the exposome, to incorporate a wider range of exposure scenarios, and to approach samples obtained without specific targeting of known pollutants [42–46]. All of these approaches have great potential for addressing complex challenges, such as those presented by UGD.

A common finding in North American and European reviews of the potential health effects of UGD is that adequate data are not available to make a conclusive assessment [47–55]. This lack of evidence has hurt the industry, notably in the decision of the Governor of New York not to go forward in shale gas development because of a New York Department of Health finding of inadequate evidence that human health would not be affected; an adverse Pennsylvania Supreme Court Decision in which the Chief Justice found that the state had failed in its responsibility to perform the necessary studies; and in European governmental decisions which have stopped or slowed what was initially a positive response to the opportunities to exploit shale gas resources as a counterbalance to purchasing natural gas from Russia [25, 26].

Epidemiological studies evaluating potential adverse consequences in humans or ecosystems require some way of categorizing the extent of exposure. Exposure to the receptor can be modeled starting with information obtained at any point beginning with the source and ending with the impact on the receptor [6, 7]. Among the notable accomplishments of exposure science in the past 30 years has been the development and validation of techniques that reliably predict exposure to the receptor without the need to directly measure the pollutant of interest immediately external to the receptor or within the receptor using a biological marker. Sutton's law can readily be violated for a standard point source for industrial emissions. Unfortunately, such indirect approaches are difficult to apply to UGD because of the four criteria listed in Table 1 and described above. The context that has led to considering the application of Sutton's law to UGD in Pennsylvania also includes speed of development of a rapidly advancing technology in a populated area without a recent history of oil or gas drilling, which has led to significant public concern about exposure and health effects.

These four criteria may interact with each other. For example, the temporal pattern of pollutant levels in relation to the activity of the receptor can depend upon both the toxicology of a pollutant of concern, such as that for carbon monoxide for which the 8 h standard is largely based on the time of equilibration between an ambient CO level and the oxygen-combining site of human hemoglobin, or on the relation between the ambient pollutant levels and human activity factors, such as for ozone in which the change of the averaging time for the ozone standard from 1 to 8 h was partially based on recognition that ozone elevations usually occurred on warm summer days when children were likely to be out of doors exercising [56]. For UGD, uncertainties about the temporal pattern of release caused by lack of transparency are compounded by lack of knowledge of which pollutants to measure.

Also of importance are practical considerations that affect the choice of monitoring techniques, for example, the often greater cost of personal monitoring coupled with the impediments placed by the need to obtain informed consent may limit the use of direct measurement of human exposure [57]. Similarly, a factor governing the choice of the exposure technique is the extent to which the goal of the study is to determine the maximum exposed individual or a population-based percentage.

One of the most important implications of the existing literature to assessing exposure from UGD activities is the extent of site to site variability. The work of Macey et al. confirm the conclusion of significant variability and suggest an approach that is more in keeping with Sutton's Law [58]. The authors review many of the causes of variability in airborne emissions and report their findings showing a wide range of air toxics levels, some said to exceed federal guidelines, measured in grab samples and passive

monitoring near oil and gas production sites in four states. Their data was obtained through a community-based approach to selecting monitoring sites and through the use of trained community volunteers to obtain the samples. Community-based citizen science is growing in use, including work on shale gas exposure by Brown and his colleagues [59, 60]. With careful attention to data quality issues, citizen science may allow more effective application of Sutton's Law in situations such as UGD.

Biological monitoring for exposure is also an effective means of applying Sutton's Law. It is used effectively in a number of situations, such as testing for childhood lead exposures where the blood lead level integrates exposure across numerous potential sources in different media; or in workers exposed to benzene as a reinforcement for standard industrial hygiene measurements of workplace benzene levels. Biological markers are most effective when they reflect exposure in ways that predict effects, such as for carboxyhemoglobin which is an integrated measure of exposure to carbon monoxide during the preceding 8–12 h, as well as a being directly involved in the pathogenesis of the overt effect. For UGD the use of biological markers is complicated by uncertainty as to what and when to measure. But concerted efforts in cooperation with transparency about the compounds associated with UGD and the time of release may meet this challenge. Biological monitoring of animals may also be helpful to understand community exposure [61].

One of the key attributes of exposure science is that it brings together a broad range of expertise. As a generalization, those with more knowledge of technology, such as engineers, contribute primarily to understanding the earliest parts of the exposure continuum beginning with the processes that lead to pollutant release, while those with more expertise about the biological sciences, such as health professionals or ecologists, are more knowledgeable about the receptors of concern. It has not helped that health professionals or exposure scientists have not been part of governmental advisory deliberations related to shale gas drilling. Recognizing the public's concern, in 2011 President Obama and the Governors of Maryland and Pennsylvania each appointed committees to provide advice on shale gas activities. Each of the three executive orders establishing these committees specified that advice was needed on health issues. Yet none of the 52 members of the three advisory committees had any expertise in health or exposure assessment whatsoever [62]. Further, neither state included their Departments of Health among the state agencies involved. Similarly, President Obama gave leadership to the Department of Energy with required involvement of EPA and the Department of Interior, but not the federal Department of Health and Human Servicesalthough NIEHS has supported important UGD-related research. Recommendations related to health surveillance studies, including exposure assessment were not followed [63]. More active inclusion of health professionals in deliberations about UGD is needed to ensure assessment of exposure pertinent to evaluating potential health effects.

Sutton's law is not original to the professions of bank robbing or of medicine. Ockham's Razor, which usually refers to favoring the hypothesis that makes the fewest assumptions, can also be considered as a principle of parsimony in which a direct approach is favored over one that is indirect, and simplicity is favored over complexity. Karl Popper, a philosopher of science, pointed out that, all other things being equal, the simpler hypothesis was favored as it was easier to test, i.e., its validity was more readily subject to falsification than a more complex hypothesis [64]. In essence, the hypothesis that humans or ecosystems are adversely affected by a new technology, such as shale gas drilling, is easiest to discard if humans and ecosystems are directly observed and found to be unaffected. Or, if stated in terms of the null hypothesis, namely that the new technology will not adversely affect ecosystems or public health, then the simplest way to test that null hypothesis is to evaluate these potential receptors.

Conclusion

Risk management focusing solely on the potential source of the risk is much more reasonable if the source is a standard technology with limited well-defined pathways for adverse consequences, which can be readily observed or monitored. If drilling deep underground for tightly bound shale gas was equivalent to the production of a standard widget, which could only fail in one way, we would just assume that previous evidence that producing the widget was safe would be sufficient to predict future safe usage, and, as a backup, would monitor releases from the single potential failure pathway.

I am not arguing that all industrial sources that potentially have environmental health consequences need to be studied by direct evaluation of potential ecosystem or human health receptors. For example, a highly touted benefit of shale gas extraction to Pennsylvania has been the decision to site a multi-billion dollar ethane cracking plant to produce feedstock for plastics [65]. The two major distinguishing features between the cracker plant and the nearby Marcellus shale drilling activities include a long past history of evaluating the emissions from such plants. There are specific national requirements under the Clean Air Act, the Clean Water Act, the Emergency Planning and Community Right-to-Know Act, as well as state laws, from many of which the drilling industry is exempt. These requirements produce an understanding of the expected

emissions from each site. Another major distinction is that there will be at most a few such plants in a region, which is anticipated to have literally tens of thousands of separate drilling sites. It is possible to argue that existing environmental regulations, including monitoring of ambient media, should be sufficient for the cracker plant without necessarily requiring major studies of ecosystems and humans. This contrasts with Pennsylvania counties which within a few years may have over a thousand well sites drilled by perhaps more than a dozen different drilling companies with differing safety cultures and techniques, using different hydrofracturing chemicals and different wastewater disposal practices. Without more direct approaches to measuring exposure, it will be difficult to establish cause and effect relationships, if they exist. If UGD supporters are correct that UGD is without human health consequence, the lack of support for systematic study of potential exposures or effects that could provide direct evidence to prove them right has come back to hurt the industry in the United States and globally [25].

Understanding the implications of Sutton's Law to exposure assessment could help focus scientific and regulatory efforts on effective approaches to evaluate the potential health and ecosystem implications of new and evolving technologies such as UGD. The growing use of citizen science and other community-based approaches, provided that they are approached with the rigor expected of exposure science, may provide valuable, and valid exposure information when the criteria to violate Sutton's Law are not met [66].

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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